Measures of symmetry in gait

Methodological principles and clinical choices

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Contents

Abstract

Aim Papers I-III:
The aim of this thesis is to evaluate measures of gait symmetry in subjects with disease or injury related to one-sided affection. This thesis also aims to relate objective measures of gait quality (gait symmetry) to other more frequently used measures of function (gait velocity) and self-reported function in patients with disease or injury resulting in asymmetric gait. Finally, this thesis aims to emphasize how methodological and clinical perspectives and demands related to the exactness of objective measurements and clinical applicability may be united, although often considered incompatible.

Paper I
Methods: Reliability and discriminating ability of anteroposterior (AP), vertical (V) and mediolateral (ML) trunk movement and single support (SS) and step length (SL) footfall symmetry measures were assessed using triaxial accelerometers and an electronic walkway. Data from 20 chronic stroke patients and 57 controls who walked six times back and forth a 7 meter walkway at self-selected slow, preferred and fast gait velocities were evaluated. The chronic stroke patients repeated the procedure three times for the test-retest reliability evaluation.

Results showed excellent test-retest reliability of all symmetry measures (ICC=0.92-0.96). Neither single support nor step length gait symmetry showed significant ability to discriminate between the two groups (AUC=0.62 and 0.53), while AP, V and ML trunk symmetry measures showed high discriminative ability (AUC=0.82, 0.90, and 0.76).

Paper II
Methods: Discriminating properties of AP, V and ML trunk symmetry, SS and SL footfall gait symmetry measures were investigated on 37 patients with hip OA and 56

controls, following similar procedures as described in Paper I. Thereafter, it was assessed whether a 10% cut-off value is valid as a general criterion of pathological gait asymmetry across measures, rather than specific calculations of optimal criteria calculated for each symmetry measure in question.

Results showed high to excellent discriminative ability of all symmetry measures. Highest discriminative ability was seen in AP, V and SS symmetry measures (AUC=0.91, 0.92 and 0.86), while discriminative ability in ML and SL symmetry measures were lower, but also significant (AUC=0.77 and 0.76). The general 10% criterion of gait asymmetry and the optimal cut-off criteria calculated for each symmetry measure showed approximately equal total classification ability. However, the optimal cut-off criteria classified a high number of controls as having pathological gait asymmetry.

Paper III

Methods: Changes in AP, V and ML trunk symmetry, SS and SL footfall symmetry during gait, gait velocity and self-reported function were assessed in 34 hip osteoarthritis patients (OA) before and 3, 6 and 12 months after total hip replacement (THR). Changes were reported in relation to time (months post surgery) and magnitude for change (ES). The gait assessment procedures at each test occasion were similar to procedures in Papers I and II. However, procedures in Paper III also included assessment of gait velocity and the distribution of Hip disability and Osteoarthritis Outcome Score questionnaires (HOOS) for self-reported function at each test occasion.

Results showed improvement in all measures from preoperative to 12-months postoperative assessment, with ES >0.30. Improvements were significant for all outcome measures, except ML symmetry. Measures of self-reported function demonstrated largest improvement with ES of approximately 0.62 in all sub-scales. In general, gait symmetry and gait velocity demonstrated largest improvement 6 and 12 months postoperatively, while self-reported function improved most 3 months postoperatively.

Conclusion Papers I-III

Symmetry measures evaluated in this thesis have excellent test-retest reliability. Discriminative ability of trunk symmetry measures is good to excellent in hip OA patients and in chronic stroke patients when compared to controls, while footfall symmetry measures showed good to excellent discriminative ability in hip OA patients, but not in chronic stroke patients when compared to the same group of controls. The results suggest that patterns of gait symmetry differ between patients with dissimilar diseases that cause one-sided affection. Measures of gait symmetry, gait velocity and self-reported function represent different aspects of function that are of high importance for patient satisfaction during rehabilitation. Self-reported function showed early improvement post THR, suggesting immediate relief from stiffness and pain, while gait symmetry and velocity improved later postoperatively, suggesting that gait quality and performance may benefit from prolonged rehabilitation with postoperative guidance, muscular strengthening and motor relearning. There is a need to include assessment of trunk movements in gait symmetry evaluation, due to compensatory movements of the upper body seen in patients with disease or injury leading to one-sided affection. Also, evaluation should include measures of gait velocity and self-reported function to provide a thorough evaluation, necessary in preparation of individually targeted rehabilitation programs. The gait evaluation methodology and protocol used in this thesis may be implemented in research as well as in clinical practice as thorough evaluations may be administrated within 15 minutes, at low cost using transportable equipment.

List of publications

Hodt-Billington C, Helbostad JL, Moe-Nilssen R (2008): “Should trunk movement or footfall parameters quantify gait asymmetry in chronic stroke patients?” Gait Posture, Vol. 27: 552-8

Hodt-Billington C, Helbostad JL, Vervaat W, Rognsvåg T, Moe-Nilssen R (2011): "Criteria of gait asymmetry in patients with hip osteoarthritis.” Physiotherapy Theory and Practice. Early on line, 1-8. DOI:10.3109/09593985.2011.574783. In press

Hodt-Billington C, Helbostad JL, Vervaat W, Rognsvåg T, Moe-Nilssen R (2011): Changes in gait symmetry, gait velocity and self-reported function following total hip replacement.” Journal of Rehabilitation Medicine, Vol. 43 (9): 787-93

Abbreviations

ADL	Function in daily living (HOOS)
ANOVA	Analysis of variance
ANCOVA	Analysis of covariance
AP	Anteroposterior
AUC	Area under the curve (ROC analysis)
FAC	Functional Ambulation Categories
HOOS	Hip disability and osteoarthritis outcome score
ICC	Intraclass correlation coefficient
MCID	Minimal clinically important difference
ML	Mediolateral
OA	Osteoarthritis
P	Pain (HOOS)
QOL	Hip-related quality of life (HOOS)
RMI	Rivermead Mobility Index
ROC	Receiver operating characteristic
ROM	Range of motion
S	Other symptoms, including stiffness (HOOS)
SD	Standard deviation
SE	Standard error
SI	Symmetry index
SL	Step length
SP	Function in sport and recreation (HOOS)
SS	Single support
THR	Total hip replacement
V	Vertical
WOMAC	Western Ontario and McMaster University osteoarthritis index
3D	Three- dimensional

Introduction

This thesis consists of three papers derived from two projects carried out in the period of 2004-2011 at the Physiotherapy Research Group, Department of Public Health and Primary Health Care, University of Bergen.

Gait symmetry is frequently assessed and reported by physiotherapists, physicians and researchers in clinical settings and in gait laboratories. There is a general agreement that gait symmetry should be a goal after disease or injuries that have lead to one-sided affection, since achievement of gait symmetry may prevent further overuse injury or disease caused by misalignment. However, there is no consensus regarding how gait symmetry should be assessed and evaluated, or on criteria for pathological gait asymmetry that requires intervention.

The tools and methodology used to assess gait symmetry may often be arbitrary. In gait laboratories, often staffed by a combined technical and clinical team, the methodology is advanced and time consuming, offering accurate gait estimations based on methodology not applicable for clinical practice due to complexity, labor and cost intensity. Hence, in clinical settings, methodology is often limited to subjective observational evaluations. The use of triaxial accelerometry in analysis of trunk movement during gait has become increasingly popular as it is easily adopted to clinical settings as well as to patients' homes or elsewhere in the community where ambulation normally take place. Along with assessment of symmetry in footfall patterns by transportable electronic walkways, a thorough and objective analysis of gait quality may be feasible to administer in clinical settings as well as in laboratories.

Before triaxial accelerometry and electronic walkways may be implemented in clinical gait symmetry evaluation, there is a need for further investigation of measurement properties. It is unknown whether trunk and footfall symmetry measures demonstrate adequate sensitivity and specificity to recognize gait in patients with unilateral disease or injury from able-bodied gait. There is a need to investigate how much deviation from perfect symmetry one should expect in able-bodied gait and when asymmetric gait should be considered pathologic, hence require intervention. Finally, unilateral disease or injury such as hip osteoarthritis (OA) may be followed by surgery such as total hip replacement (THR). Hence, there is a need to know when or if one can expect postoperative change or improvement towards gait symmetry after surgery, as well as the magnitude of change in gait symmetry and other frequently used measures such as gait velocity and self-reported function at different time-points after surgery.

The present thesis will hopefully increase awareness and knowledge about the importance of including gait symmetry evaluation in patients with disease or injury causing one-sided affection. The aim of this thesis is to evaluate measures of gait symmetry in subjects with disease or injury related to one-sided affection. This thesis also aims to relate objective measures of gait quality (gait symmetry) to other more frequently used measures of function (gait velocity) and self-reported function in patients with disease or injury resulting in asymmetric gait. Finally, this thesis aims to emphasize how methodological and clinical perspectives and demands related to objective measurements and clinical applicability may be united, although often considered incompatible.

1. Background

1.1 History of gait analysis

The first experimental gait analyses were performed by Giovanni Borelli (1608-1679), an Italian physiologist, physicist and mathematician who introduced mathematical concepts of muscle and tendon biomechanics in the 17^{th} century. One of Borelli's first conclusions was that there is mediolateral (ML) movement of the head during gait (Baker, 2007). These principles of Borelli's were additionally inspired by discoveries of Rene Descartes' (1596-1650) coordinate geometry describing the position of objects in space and Isac Newton's (1642-1727) mechanics linking kinetics and kinematics (Force=mass·acceleration) (Baker, 2007, Sutherland, 2001). Experimental work on how step length and cadence change with walking speed, was first reported by Ernst Heinrich Weber (1795-1878) and his brother Eduard Friedrich Willhelm Weber (1806-1871), using a stop watch, measuring tape and a telescope as tools (Baker, 2007).

Three-dimensional (3D) gait analysis was introduced by the German anatomist Christian Wilhelm Braune (1831-1892) and the mathematician Otto Fischer (1891-1917) (Baker, 2007). They applied Geissler tubes to the limb segments and positioned four cameras around the subjects, one in front, one on the back and one on each side, providing tri-dimensional measurements. Subjects walked in darkness wearing rubber suits to avoid electrical shock (Sutherland, 2002).

In the 19^{th} century Braun and Fischer introduced presentations involving estimates of muscle actions, with the purpose to create elegant representation of gait in military subjects carrying backpacks (Sutherland, 2001). However, the methodology was very labor intensive and not applicable for use in clinical settings (Sutherland, 2001, Sutherland, 2002). Nicolai Bernstein (1896-1966) modified their work and made gait analysis of older people and children possible. He also suggested the previously introduced movement in the ML direction as unimportant during gait (Baker, 2007).

The early gait analysis had been driven by scientific curiosity rather than by clinical need. However, after the First World War, the French rehabilitation specialist Jules Amar (1879-1935) developed the three component force plates. Amar was driven by clinical rather than scientific curiosity, and wanted to measure rehabilitation of those injured during the war (Baker, 2007). In the 1940s, Vern Inman (1905-1980) introduced measures of muscle activation signals (EMG) in relation to energy measures and joint movement during gait (Kinesiological electromyography, KEMG). The method was used on healthy subjects and amputees, but was painful as bone pins were inserted to act as markers of skeletal position during gait. Later, in 1957 David H. Sutherland (1923-2006) introduced EMG data synchronized with movie films during walking. While most of the early studies were carried out on patients in rehabilitation from poliomyelitis, the study population changed to patients with cerebral palsy in the mid-60s. However, the applied methodology was still too labor intensive, invasive and computationally demanding for use in clinical settings (Sutherland, 2001).

Commercially available force plates were invented by Walter P. Kistler (1918-) in 1969 (Baker, 2007), and followed by the footswitch, invented by physiotherapist and medical doctor Jacquelin Perry (1918-) about 1970 in collaboration with the electrical engineer Dan Antonelli. The foot switches were the first method that did not depend on intensive labor. It allowed assessment of temporal measures, and became the basis of the Stride Analyzer refined by Ernest Bontrager and still widely used throughout the world (Sutherland, 2001), with the latest version released in 2010 (P & L Engineering, 2011).

In clinical settings, gait evaluation remained primarily on clinical observation throughout the 1970s. Observational methodology was said to become an art after years of continued practice and clinical application, but information could not be quantified (Robinson and Smidt, 1981). A clinically feasible method to provide objective, quantitative information on gait variables such as cadence, velocity, step length and stride length was therefore proposed by James Robinson and Gary Smidt (Robinson and Smidt, 1981). The variables were assessed as patients crossed a grid patterned walkway. The therapist walked closely behind the patient calling out heel-strike locations from the grid pattern into a tape recorder. A stop watch was used to record time between the first and last heel strikes (Robinson and Smidt, 1981). The methodology was furthered by introducing soft heel counters with dye or inkpads fixed to the bare feet with Velcro, giving readable marks on paper walkways, or simply walking on talcum powder (Helbostad and Moe-Nilssen, 2003, Stolze et al., 1998, Whittle, 2007, Rose GK, 1983). These time-consuming manual recordings have later been replaced by electronic walkways capable to measure timing of foot contact and positioning of the foot during gait. Many of these walkways were built and specifically designed for single laboratories (Whittle, 2007). A number of commercial systems are now available, the GAITRite system being one of the most commonly used (Menz et al., 2004, Whittle, 2007, Bilney et al., 2003)

Accelerometers used to quantify and describe gait patterns was first introduced by Wladimir Theodore Liberson (1904-1994) in the 1930s (Kavanagh and Menz, 2008). The introduction of advanced mathematical techniques along with advances in computer technology furthered the use of accelerometry in the examination of walking in the 1960s and 1970s (Kavanagh and Menz, 2008). Increased processing power, greater sampling rates and data resolution improved the data storage technologies during the 1990s, and made the usability of data logging systems better as it lowered the cost and decreased the size of the body fixed sensors (Anderson and Lyons, 2001). Kamiar Aminian introduced a methodology that enabled the detection of gait cycle phases, including gait symmetry, using two miniature uni-axial accelerometers fastened on the thighs. Sagittal plane measures stored in memory cards allowed up 12 hours of recordings within gait laboratories or in clinical settings (Aminian et al., 1999). From the use of several uniaxial sensors attached using double sided tape, The DynaPort accelerometer methodology as introduced by Rob C. Van Lummel (McRoberts B V, The Hague, Netherlands), offered small three-dimensional accelerometers easily attached using elastic belts (Veltink et al., 1996) (, 2011).

Commercially available general-purpose data logger for gait analysis was first used by Rolf Moe-Nilssen (1998c, 1998b, 1998a, Anderson and Lyons, 2001). Moe-Nilssen also demonstrated that trunk accelerometry is a reliable and sensitive method for assessment of balance during stance or gait in a variety of physical contexts (Moe-Nilssen, 1998a, Moe-Nilssen, 1998b, Moe-Nilssen, 1998c). The recent evolution of accelerometer technology has been said to represent a paradigm shift in the quantification of gait and movement disorders (LeMoyne R et al., 2008). New technology allows collection of quantitative data representing full gait cycles of unrestricted movement in natural environments at low cost (LeMoyne R et al., 2008). Figure 1 displays the increased use of accelerometers in gait evaluation and balance control, indicated by number of publications per year from 1981 to 2010.

The methodology of gait analysis is highly improved from the early stages of clinical gait analysis and involves a large number of assessment tools, many of which may still be time consuming, labor intensive to use and limited to settings which have little in common with daily requirements of performance (Paul, 1989). To systematize the several objective measurement systems that were developed during the 20th century, Jacquelin Perry suggests five categories, as modified in Table 1 (Perry, 1992). The first three categories include motion analysis, dynamic electromyography (EMG) and force plates, which focus on one facet or one specific event during gait. The two latter, measures of stride characteristics and gait efficiency, summarize the effect of gait mechanics (Perry, 1992). In this thesis, it is suggested to include measurement properties of segmental acceleration and gait efficiency recorded by body fixed sensors using modern accelerometers in category 5.

Body fixed accelerometers combined with an electronic walkway are used to assess gait symmetry in this thesis. Hence, further attention involving the other measurement categories reported in Table 1 is beyond the scope of this thesis.

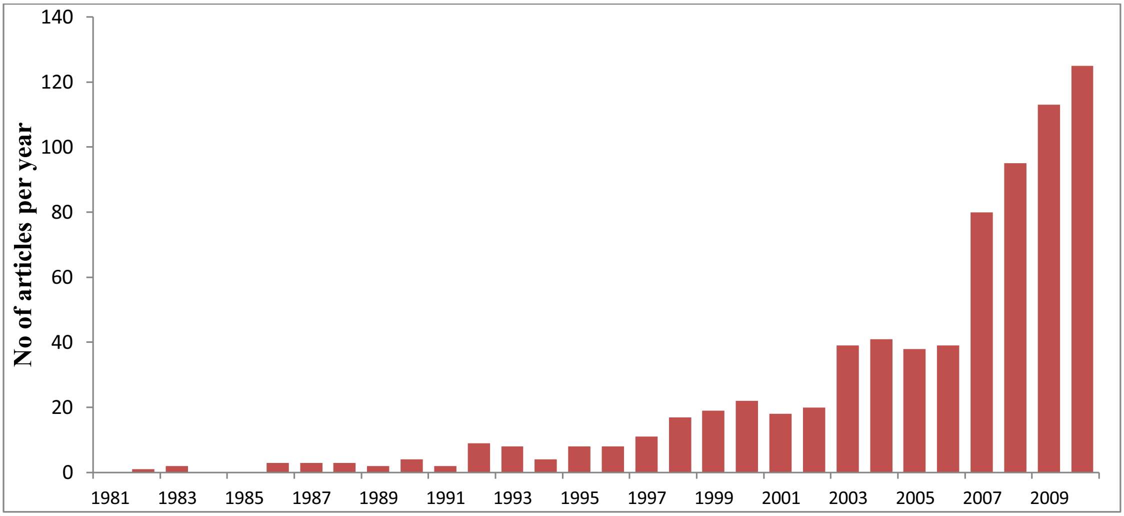

Figure 1. Number of publications on accelerometry and balance control from 1981 to 2010. Search criteria Pubmed: (accelerometer OR accelerometry OR trunk acceleration) AND (balance OR standing OR gait OR walking OR sway)

Table 1: Categorization of objective measurement systems developed during the 20th century[1].

Measurement categories		Properties
1	Motion analysis (including three-dimensional (3D) camera systems)	Pictures that can record movements of the whole body. Often used to evaluate magnitude and timing of individual joint movement (Watelain et al., 2001)
2	Dynamic electromyography (EMG)	Record indirect identification of period and relative intensity of muscle function
3	Force plates	Record ground reaction forces (GRF) generated as the body weight drops onto and moves across on the supporting foot. The force plates are often used in combination with camera systems (Watelain et al., 2001)
4	Electronic walkways and footswitches	Record stride characteristics
5	Body fixed sensors/accelerometers	Record energy cost during gait and/or segmental accelerations during walking

[1]Categories modified from Perry (1992).

1.2 Gait symmetry

Gait symmetry is considered an indicator of normal walking and may serve as a diagnostic tool for clinicians. Normal walking has been defined as:

> *"A method of locomotion involving the use of the two legs, alternately, to provide both support and propulsion, with at least one foot being in contact with the ground at all times (Whittle, 2007)"*

The terms walking and gait are often used interchangeably, however gait describes the style or technique of walking rather than the walking process itself (Whittle, 2007). The gait cycle (GC) is the time interval between two successive occurrences of one of the repetitive events of walking, for instance initial heal contact (Whittle, 2007). In symmetric gait, the gait cycle consists of a stance (60-62% of the GC) and a swing (40%) phase. The stance phase is further divided into double limb (20%) and single limb (40%) support phases where respectively both feet and one foot is in contact with the ground. The single limb support phase may also be referred to as the opposite limb's swing phase (Kirtley, 2006). Step length is the distance from one foot strike to the foot strike of the other foot, while stride length is the distance from one heel strike to the next heel strike by the same foot (Shumway-Cook and Woollacott, 2007). In symmetric gait, the two consecutive steps involved in one stride will be of approximately equal length (Whittle, 2007). Throughout the GC, the upper body moves up and down, forward, from side to side, and twists about the vertical axis, the shoulder girdle rotating in the opposite direction to the pelvis (Whittle, 2007). Movement, or symmetry of movement, of the upper body during gait has often remained unexplored in previous research (Whittle, 2007).

In Encyclopedia Britannica (Symmetry, 2010) symmetry is defined as the correspondence of body parts in size, shape, and relative position, on opposite sides of a dividing line or distributed around a central point or axis (Symmetry, 2010). Asymmetry on the other hand, is simply defined as the absence of symmetry (Asymmetry 2010). In previous research, gait symmetry is considered present when equal values, or no statistical differences, of gait variables exist on both sides of the body (Hesse et al., 1997, Griffin et al., 1995, Gundersen et al., 1989, Herzog et al., 1989).

Measures frequently use in gait symmetry assessment include step length (Patterson et al., 2010b, Allen et al., 2011, Balasubramanian et al., 2007), single limb support (Patterson et al., 2010b, Wykman and Olsson, 1992), pelvic and/or trunk movement (Vogt et al., 2003, Tura et al., 2010, Watelain et al., 2001), and ground reaction forces (Table 1). In this thesis, gait symmetry assessment is limited to measures of step length, single support and trunk movement in anteroposterior, vertical and mediolateral direction.

Gait symmetry seems to be consistent regardless of age and gender (Jansen et al., 1982). This is in contrast to age- and gender related differences normally seen in other gait measures. Cadence and time spent in double limb support increase with increasing age, while reduced gait velocity is seen in the elderly compared to the young and in women compared to men (Shumway-Cook and Woollacott, 2007, Winter DA., 1991, Eppeland et al., 2009). In normal gait, as well as in gait evaluation of patients after disease or injury, a certain level of gait asymmetry should be considered normal (Sadeghi et al., 2000). Hence, complete symmetry in human movement is unlikely, as structural asymmetry in limb length without underlying disease or injury is present in 90 % of the population, with an average magnitude of 5.2 mm (Knutsen, 2005a). It has been stated that limb inequality of 20 mm must be present before such differences may be considered clinically significant (Knutsen, 2005a). Reliable assessment of limb length inequality is difficult to perform clinically, partly because of putative biomechanical adaptations (Knutsen, 2005b). Functional asymmetry is also called unloaded leg-lengths asymmetry (Knutsen, 2005b) and is often a result of preferential use of one limb in motor tasks, such as writing or skipping on one foot. Functional asymmetry related to limb preference and laterality in healthy subjects usually represents non-pathologic levels of asymmetry (Sadeghi et al., 2000).

1.3 Psychometric properties of symmetry measures

Measures of gait symmetry may contribute to insight about the quality of gait (Patterson et al., 2008), unique from the conventional measures of functional performance. However, it is a prerequisite that measures used in gait evaluation possess good reliability and validity. Reliability of clinical measures tells us how reproducible the result from a measure are under different conditions (Streiner and Norman, 2008), and may be reported as retest reliability, comparing test results on successive occasions statistically (Moe-Nilssen et al., 2008, Streiner and Norman, 2008). Among statistical procedures, the intraclass correlation coefficient (ICC) analysis is frequently used to evaluate reliability of a measure, also reflecting the variability in data caused by specific measurement error to total variability (Moe-Nilssen et al., 2008). Content validity of a measure means whether the measure actually measures what it is intended to measure (Streiner and Norman, 2008, Field, 2009).

Psychometric properties of screening tools are often described using sensitivity and specificity of how a certain test result relate to normality or abnormality (Deeks and Altman, 2004), or rather normal or pathologic gait asymmetry. Hence, discriminating ability of a measure is the measure's ability to correctly classify a group of patients with gait asymmetry from a group of controls with normal gait. Such classification is dependent upon the limit or cut-off chosen to separate the two groups, for instance the level of gait asymmetry required before gait is considered pathologic. The receiver operator characteristic curve analysis (ROC) is suitable for this purpose, as illustrated in Figure 2. A measure with good discriminating properties would have a trace that passes close to the upper left corner of the graph (illustrated by the solid line in Figure 2), while a measure that is no better than one would expect by chance alone, is represented by a diagonal line (as illustrated by the dotted line in Figure 2).

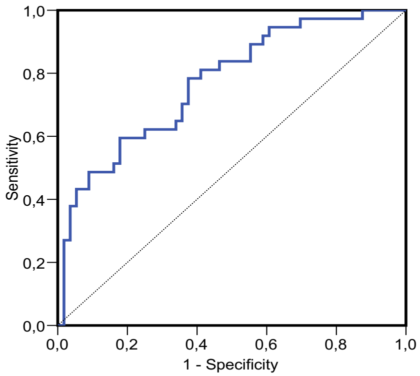

Figure 2: Receiver Operator Characteristic (ROC) curve illustrating a measure's ability to evaluate discriminative properties of a measure

Some measures may be more sensitive to change than other measures (Streiner and Norman, 2008). To evaluate change in gait symmetry over time, change should be assessed in a population expected to experience change, such as patients with hip OA undergoing THR. Whether this change occurs spontaneous or as a result of intervention is not important in a validity study (Moe-Nilssen et al., 2008). There is no universal consensus on how to report change, but there is often a need to create dimensionless ratios, which are possible using varieties of effect size (ES) calculations, originating from Cohen's (ES=(average change)/SD) (Cohen 1988). There is no consensus regarding how much change that is required to achieve "enough" change, but it has been suggested that a change equal to Cohen's ES of 0.5 may be a reasonable first approach to a threshold (Streiner and Norman, 2008).

1.4 Gait symmetry assessment

Gait symmetry is frequently assessed and described in patients with one-sided injury or disease (Vogt et al., 2006, Watelain et al., 2001), and is often an advocated goal for physical therapy after disease or injury affecting lower limbs, such as stroke and hip OA (Vogt et al., 2006, Hodt-Billington et al., 2008). Cadence, stride length and gait velocity have been referred to as general measures of gait (Whittle, 2007). The measures are frequently used in gait evaluation, alone or in combination with other outcomes measures, such as stride to stride variability assessed by accelerometers and often used in evaluation of balance control and fall prevention (Helbostad et al., 2007, Kressig and Beauchet, 2006, Moe-Nilssen and Helbostad, 2002). In symmetry evaluation, footfall measures such as step length, step time and single (limb) support may provide separate descriptions of each leg or side of the body, and is frequently described (Roerdink and Beek, 2011, Balasubramanian et al., 2007, Senden et al., 2009, Tyson, 1994, Vogt et al., 2006), often along with asymmetries in accelerometer based outcomes of trunk movement patterns (Tura et al., 2010, Moe-Nilssen and Helbostad, 2004) and also along with measures of dynamic joint loads/ground reaction forces (Shakoor et al., 2003, Herzog et al., 1989). As such, the interest in objectively assessed gait symmetry is increasing. But most research on patients with unilateral impairment limit reports of function to self-report questionnaires along with measures of gait velocity, mean step length (without symmetry considerations), tests of endurance and other functions (Lavigne et al., 2010). Objective measurement tools may provide a neutral evaluation which is easily communicated and support clinical decision making and treatment planning as well as aid discussions with other professionals, patients and their families (Tyson et al., 2010). Objective evaluation of biomechanical joint movement are frequently performed and often presented in symmetry related terms (Le Duff et al., 2009), especially in orthopedic disease or injury. Even though biomechanics of one joint is often reported in relation to the contra-lateral joint, joint or limb movements are often measured isolated from movement pattern of the body as a whole, ignoring differentiation between strategies used to propel limbs forward (Allen et al., 2011, Hodt-Billington et al., 2008, Perry, 1992, Watelain et al., 2001). Little effort has been made to specifically quantify asymmetry (Allen et al., 2011, Patterson et al., 2008). There is a need for outcome measures that address gait abnormalities such as asymmetry in weight bearing and step lengths (Cibulka et al., 2009), related to primary and potentially compensatory movement strategies.

Despite the potential positive effects of rehabilitation strategies and targeted rehabilitation programs, no commonly accepted superior guideline, preferred methodology or protocol exist for gait symmetry evaluation. The European GAITRite Network Group, developed *Guidelines for Clinical Applications of Gait Analysis* (Kressig and Beauchet, 2006), with the intension to facilitate collaboration and provide guidance to clinicians who wish to implement spatio-temporal gait analysis to their clinic. In the guideline, two issues are addressed 1) Environmental measurement conditions and safety issues, includes lighting, noise and visual distraction, clothing and footwear and safety. 2) Measurement procedures, including steady-state gait at different velocities, standardized walking instructions, assistive devices, stride-to-stride variability, gait analysis in association with simultaneous cognitive tasks and description of study population. Even though many issues in the guideline are highly relevant in gait symmetry assessment, further development of procedures for gait symmetry assessment still remains.

1.5 Symmetry indices

Patterson et al. (2010b) suggest that choice of equation used to calculate symmetry is one components of a symmetry measure, while the parameter used in the equation is the second component. The equations used to calculate and/or present symmetry are often referred to as symmetry indices. A number of symmetry indices are previously used (Table 2), however all indices have known limitations (Sadeghi et al., 2000). The frequent categorization related to affected or unaffected limbs in patients, or right and left limbs in controls, may even out the true magnitude of asymmetry if patients with opposing directions of gait asymmetry are included in mean value calculations. The effect of the direction of gait asymmetry may be eliminated by the use of absolute values in the symmetry indices (Zifchock et al.,

2008) or by the use of lower and higher limb values as described in formula no 2, Table 2, rather than limbs categorized in relation to disease or injury. Patterson et al. (2010b) evaluated four frequently used symmetry indices after assessing spatiotemporal gait measures in patients post stroke: The symmetry ratio (formula 1, Table 2), Robinson symmetry index (formula 3), a log-transformed symmetry ratio and symmetry angles (formula 4). In conclusion, the authors chose to advocate the ratio index for footfall measures, as it was found valid and easy to implement and interpret in regard to performance of limbs or movement qualities during gait (Patterson et al., 2010b).

Table 2: Equations frequently used to calculate and quantify symmetry in gait

Formula name:	Number	Equation
Symmetry ratio$_{footfall}$	1a:	$SI=\left\lvert 1-\frac{\text{Uaffected limb}}{\text{Affected}}\right\rvert$
	1b:	$SI=\left\lvert 1-\frac{\text{Affected limb}}{\text{Unaffected}}\right\rvert$
	1c:	$SI=\left\lvert 1-\frac{\text{Left limb}}{\text{Right limb}}\right\rvert$
Symmetry ratio$_{footfall}$	2	$SI=\left\lvert 1-\frac{\text{Limb with lower value}}{\text{Limb with higher value}}\right\rvert$
Robinson index	3	$SI=2\frac{X_{unaffected}-X_{affected}}{X_{unaffected}+X_{affected}}\cdot 100$
Log transformed	4	$SI=\left\lvert 100\cdot\left(\ln\left(\frac{X_{affected}}{X_{Unaffected}}\right)\right)\right\rvert$
Symmetry angle	5	$SA=\frac{[45°\text{-arctan }(X_{Affected}/X_{Unaffected})\cdot 100]}{90}$
Symmetry index$_{trunk}$	6	SI_{trunk}=Between tride regularity-|Between step regularity|

References: 1a: (Hodt-Billington et al., 2008,Patterson et al., 2008,Madsen et al., 2004). 1b: (Balasubramanian et al., 2007, Brandstater et al., 1983). 2: (Hodt-Billington et al 2011, Hesse et al., 2003). 3: (Robinson et al., 1987, Herzog et al., 1989,Vogt et al., 2006, Roerdink and Beek, 2011). 4: (Plotnik et al., 2007). 5: (Zifchock et al., 2008). 6: (Hodt-Billington et al., 2008)

1.6 Criteria for pathologic gait asymmetry

A certain amount of gait asymmetry is usually present in able-bodied gait (Sadeghi et al., 2000), but no common agreement exists on clinical criteria for pathologic gait asymmetry. In visual observation or self-reports of physical function, gait symmetry is frequently reported as present or not present. Such reports may not satisfy scientific criteria of reliability and validity (Toro B et al., 2003), but are often done for practical or cost-effective reasons (Archer et al., 2006).

In objectively assessed gait evaluations, an arbitrary cut-off value of 10% deviation from perfect symmetry is previously used as a criterion of asymmetry in gait (Robinson et al., 1987, Balasubramanian et al., 2007). The criterion has also been criticized because of its non-parameter-specific nature (Herzog et al., 1989). A parameter-specific criterion represents the optimal cut-off value that best discriminate pathologic gait asymmetry from normal gait asymmetry for each symmetry measure. Such optimal criteria may be obtained by receiver operating characteristic analysis (ROC). Sensitivity and specificity interact, and changing the cut-point will favor one over the other. An improvement in both sensitivity and specificity would explain an overall improvement in the measures ability to discriminate pathologic gait asymmetry from able-bodied gait (Streiner and Norman, 2008). Other previously used criteria to describe the absence or presence of gait asymmetry include the use of 95% confidence intervals (CI), where gait symmetry within the limits of a 95% CI obtained in a healthy population would define able-bodied gait, while gait asymmetry outside the 95% CI would define pathologic gait (Herzog et al., 1989, Patterson et al., 2008, Patterson et al., 2010b). Finally, significant differences between limbs (Sadeghi, 2003, Wykman and Olsson, 1992) or groups (Sliwinski and Sisto, 2006, Vogt et al., 2003) may be used to define pathologic or normal gait asymmetry. Although tests of significance may be a necessary precondition, the significance criterion says nothing about the actual magnitude or the clinical importance of a difference (Norman and Streiner, 2000). Small samples may give non-significant results despite huge differences in gait symmetry, whereas large samples may result in significant differences despite small differences in gait symmetry (Norman and Streiner, 2000).

1.7 Pathological conditions associated with gait asymmetry

Pathological conditions associated with gait asymmetry were recognized in the 19th century. In France, Guillaume Duchenne (1806-1875) reported gait in children with Duchenne muscular dystrophy, where flaccid paralysis of the hip flexors made the patient unable to initiate a proper swing during gait. To compensate, they performed forward limb circumduction with raised pelvis and increased abduction (Baker, 2007). The same pattern of compensation during gait is seen in patients with hemiplegic gait after stroke, while an opposite pattern of compensations, Trendelenburg gait, is seen in patients with hip OA or in patients postoperative to THR. In Trendelenburg gait, the pelvis is dropped on the affected side and adduction is increased during stance as a consequence of functional but weak hip abductors. The gait pattern was first reported by the German surgeon Friedrich Trendelenburg (1844-1924)(Baker, 2007).

Stroke and hip OA represent diseases often related to one-sided disabilities and inefficient gait, and often relatively high oxygen consumption in relation to distance travelled (Cunha-Filho et al., 2003, Patterson et al., 2008). The mechanical factors of the asymmetric misalignment, may further lead to loss of bone mass density of the affected leg (Jorgensen et al., 2000, Liu et al., 1999), higher dynamic loading on the contralateral limb and joints, which in turn may progress osteoarthritis processes and musculoskeletal injury to the unaffected leg and joints (Shakoor et al., 2002, Shakoor et al., 2003, Block and Shakoor, 2010, Patterson et al., 2008). When evaluating measurement properties of gait symmetry measures, there is a need to involve patients with disease or injury associated with gait asymmetry.

1.7.1 Gait in patients post stroke

Today, stroke is one of the diseases with the highest incidents of death and disability in Norway. Approximately 15 000 subjects suffer from stroke every year (Helsedirektoratet, 2010). Post stroke, muscle strength is usually impaired in the affected limb, but frequently also in the unaffected limb, suggesting slower gait velocity as a result of decreased mobility as well as hemiparesis (Andrew and Bohannon 2000; Liu 1999). Preferred gait velocity of 0.56-0.73 (SD 0.24-0.33) m/s and fast gait velocity of 0.76 (SD 0.31) m/s has been reported in chronic stroke patients (Jonsdottir et al., 2009, Patterson et al., 2010a), which is slower than preferred gait velocity for healthy adults; ranging from 1.05-1.50 m/s (Perry, 1992, Jonsdottir et al., 2009, Eppeland et al., 2009, Bohannon, 1997). Gait post stroke is also characterized by asymmetry (Olney and Richards, 1996, Mauritz, 2002, Brandstater et al., 1983). Achievement of gait symmetry is suggested as a determinant of recovery after stroke (Hesse et al., 2001, Titianova and Tarkka, 1995), and failure to recover symmetric gait after stroke may lead to difficulties in balance control, loss of bone mass density of the paretic hip and increased risk of musculoskeletal pain and joint degeneration, also in the non-paretic limb (Patterson et al., 2008, Jorgensen et al., 2000).

However, the theoretical rational behind the goal to achieve gait symmetry after stroke has been questioned. On a pathophysiological basis, stroke is a result of hemorrhage or thrombus affecting the arterial supply of the brain, usually of one side, causing damage to motor cells and pathways of the central nervous system. Immediate impairments or inability to generate voluntary muscle contractions and inappropriate timing or grading of muscle activity results in impaired gait performance (Olney and Richards, 1996). As such, Olney and Richards (1996) relate bilateral function after stroke to the obvious differences in output one would expect from a machine containing two unequally powered motors. Hence, gait asymmetry becomes a positive adaptation to the neurologic deficits caused by the disease. According to this point of view, the achievement of symmetry is a matter of aesthetics, while asymmetric gait may be important in the promotion of gait velocity and other requirements for forward progression in gait (Olney and Richards, 1996).

Commonly used subjectively assessed scales in post-stroke gait evaluation, include the Barthel Index (Mahony and Barthel, 1965), the Functional Ambulation Categories (FAC), the Motor Assessment Scale (Carr et al., 1985) and the Rivermead Mobility Index (RMI) (Collen et al., 1991). However, while the FAC is the only test specific for gait evaluation (Forlander and Bohannon, 1999), only the Rivermead Mobility Index addresses gait symmetry or limping during running and also trunk, hip, knee, ankle and plantar position of the affected side.

1.7.2 Gait in patients with hip OA and THR

In Norway, 8 224 hip prosthesis (including 1 195 revisions) were operated in 2009 (The Norwegian Arthroplasty Register, 2010). Primary hip OA is a major reason for pain and disability leading to misalignment and gait asymmetry in the elderly, and the primary cause of hip replacement surgery in Norway (5 451 operations) (The Norwegian Arthroplasty Register, 2010). Gait asymmetry is frequently present in patients with hip OA (Watelain et al., 2001, Vogt et al., 2006, Lugade et al., 2010), and the achievement of symmetric gait has been suggested as a determinant of recovery in OA (Shakoor et al., 2003) and THR (Wall et al., 1981). However, studies show that asymmetric loading often sustain for years, even after successful intervention that otherwise rendered patients asymptomatic (Shakoor et al., 2003). Patients who report that they do not have a limp four years after THR, also report that the operation fulfilled most or more of the expectations they had prior to THR (Mancuso et al., 2009, Brokelman et al., 2008).

The hip joint is a ball and socket synovial joint with articular cartilage and a joint capsule allowing movement in all three body planes (Singleton and LeVeau, 1975). In hip OA, the joint structure and function is affected, with joint capsular changes creating limitation in hip joint range of motion along with subsequent articular cartilage degeneration. These changes may be followed by the development of process osteophytes, spurs and sclerosis of the subchondral bone, often involving the whole hip joint with lax ligaments, weak muscles and inflammatory infiltrates of the synovium (Felson et al., 2000).

The incidence of hip OA increases with age and is higher in women than in men (Havelin et al., 2002). Many different prosthesis and operating approaches are used in THR, but choice of THR prosthesis and operating approach do not seem to affect level of postoperative physical function and performance (Lavigne et al., 2010).

In patients after THR surgery, functional evaluation was previously done by orthopedic surgeons using tests such as the Harris hip score (Johnston et al., 1990) or survival analysis that focused on revision, radiographic images or pain as end points. Little attention was given to evaluation of gait symmetry. Nowadays, also self-report measures such as Nicholas Bellamy's Western Ontario and McMaster University osteoarthritis index (WOMAC® http://www.auscan.org/womac/index.htm) and the Oxford hip score (Dawson et al., 1996) are used for easy assessment of patients' satisfaction (Learmonth et al., 2007). The WOMAC® is a registered trade-mark measure consisting of 24 questions regarding pain, stiffness, and physical function. None of the questions address limping or asymmetry in gait. The Oxford hip score (Dawson et al., 1996) consists of 12 questions, including one question that address limping during gait. The Hip disability and Osteoarthritis Outcome Score questionnaire (HOOS) was developed as an extension of the WOMAC questionnaire. It contains all items of the WOMAC questionnaire, but also questions about hip related quality of life and sports related activities (see chapter 3.3.4) (Klassbo et al., 2003). However, gait symmetry or limping remains to be addressed, also in the HOOS.

As addressed above, the pathology and gait patterns of patients with stroke and osteoarthritis may be somewhat different even though both conditions involve unilateral affection. As such, one may not expect a uniform pattern of asymmetry between conditions. However, single support seem to be longer on the unaffected limb compared to the affected limb in patients with hemiplegic gait (Hsu et al., 2003, Olney and Richards, 1996), as well as in patients with hip OA: The direction of step-length asymmetry in patients after stroke seem to be more varied (Balasubramanian et al., 2007), but may be useful in identification of specific compensatory strategies of the trunk during gait (Roerdink and Beek, 2011, Allen et al., 2011). Potential inconsistencies in the direction of step length asymmetries in patients with hip OA remains to be further investigated.

1.8 Change in gait symmetry

To assess improvement or change in function over time, the same measures of function should be assessed on the same patients at repeated occasions. The term “repeated measurements” refers to data in which the response of each subject is observed on multiple occasions (Davis, 2002). It is the only study design that may obtain information concerning individual patterns of change. Between patient sources of variability can be excluded from the experimental error and the design provides more power to detect effects than cross-sectional designs with the same number and pattern of measurements (Davis, 2002, Field, 2009).

In post stroke gait, the conventional view has been that one should only expect improvement in gait the first three months post stroke (Jorgensen et al., 1995, Goldie et al., 1996), and gait asymmetry has been found to persist and even progress in the long term post stroke (Patterson et al., 2010a). Expected change or recovery of gait symmetry seems to differ between pathologic conditions. In patients with hip OA, gait asymmetry is often present (Vogt et al., 2006, Watelain et al., 2001), however THR is known as a highly successful intervention (Aminian et al., 1999, Brokelman et al., 2008, McConnell et al., 2001). Studies report patients to reach single support and step length symmetry levels similar to controls as soon as 16 weeks post surgery (Lugade et al., 2010), or symmetries in step length and single support throughout an assessment period ranging from preoperative to 12 months postoperative assessments (Miki et al., 2004). Asymmetries in the range of hip motion were in the same study reported to persist up to 12 months post-surgery (Miki et al., 2004). Aminian et al. (1999) found high and progressive reduction in double support and stance asymmetry assessed before and up to one year after THR. Previous studies have also shown that postoperative deficits in strength and postural control may contribute to postoperative limping persisting for two years after THR (Rasch et al., 2010) due to muscle weakness of the iliopsoas, gluteus medius and maximus and the adductors.

2. AIMS OF THE STUDY

The overall aims of this thesis were:

The aim of this thesis is to evaluate measures of gait symmetry in subjects with disease or injury related to one-sided affection. This thesis also aims to relate objective measures of gait quality (gait symmetry) to other more frequently used measures of function (gait velocity) and self-reported function in patients with disease or injury resulting in asymmetric gait. Finally, this thesis aims to emphasize how methodological and clinical perspectives and demands related to objective measurements and clinical applicability may be united, although often considered incompatible.

The aims of Papers I-III were:

Paper I: To investigate whether trunk and footfall measures recognize gait asymmetry differences seen in a group of chronic stroke patients and a comparison group with no known gait asymmetries. To identify which gait symmetry measure had the best ability to discriminate between the two groups.

Paper II: To investigate discriminative ability of trunk and footfall gait symmetry measures in patients with hip OA. To investigate if a general criterion of 10% is valid, feasible and should be preferred as a criterion of gait asymmetry across measures, compared to optimal cut-off criteria assessed for each measure.

Paper III: To investigate the magnitude of change of gait symmetry, gait velocity and self-reported function at different time-points during the first 12-months after THR.

3. Participants and Methods

3.1 Ethics

Subjects participating in the included studies have signed written informed consent prior to participation. The projects were carried out in accordance with the principles outlined in the Declaration of Helsinki, and approved by the Committee for Medical Research Ethics in Norway and the Norwegian Social Sciences Data Service (NSD).

3.2 Subjects

This thesis consists of three papers (**Papers I-III**) and includes two samples of patients (Sample I and II) and one sample of controls (Sample III). In **Paper I**, a cross-sectional study of chronic stroke patients (Sample I) was performed. Trunk and footfall gait symmetries were compared to gait in controls without injury or disease related to asymmetry (Sample III). **Paper II** is based on a cross-sectional study examining criteria for gait asymmetry in patients with hip OA scheduled for THR (Sample II). Gait symmetry in the OA patients were seen in relation to gait symmetry in the controls (Sample III), providing the basis for the proposed criteria for pathologic gait asymmetry. **Paper III** is a longitudinal study with one preoperative and three post operative test occasions examining changes in gait symmetry, gait velocity and self-reported function in patients with hip OA undergoing THR surgery (Sample II).

The selected samples of chronic stroke and hip OA patients represent patients with diseases involving one-sided pathology likely to result in gait asymmetry. Sample II, the hip OA patients about to undergo total hip replacement (THR) surgery, is chosen for the repeated measures design because THR is recognized as a highly successful intervention (Brokelman et al., 2008, Aminian et al., 1999). The controls are included based on criteria excluding any subject with history of disease or injury normally related to, or likely to cause one-sided affection.

3.2.1 Sample I – chronic stroke (Paper I)

Sample I consists of a group of 20 patients with chronic stroke (45% female), mean age 58 SD 8 years, randomly selected from inpatients with stroke at a University Hospital in Norway throughout 1996-2002 (n=337). Patients were screened according to criteria described in Table 3 and classified as having mild stroke. Included patients participated in gait analyses in 2004.

3.2.2 Sample II – hip OA (Papers II and III)

Sample II consists of hip OA patients scheduled for THR at two University hospitals in Norway. Included patients had geographic home location within the areas of the hospitals or were willing to travel to test sites. Further screening was done according to criteria described in Table 3. Mean age of osteoarthritis patients included in Paper II was 63 SD 10 years (59% female), while the mean age of patients undergoing hip replacement surgery was 63 SD 11 years (59% female). The recruitment process is displayed in Figure 3. Patients received hip prostheses as decided by the operating hospitals and listed in Table 4. Preoperative data collection (**Paper II** and **III**) was performed throughout 2005-2006 and postoperative assessments finished in 2007 (**Paper III**).

3.2.3 Sample III – controls (Papers I and II)

Sample III, the controls (**Paper I and II**) is a convenience sample recruited from subjects waiting for cataract surgery at a University Hospital in Norway (n=200). Selected subjects were thoroughly screened for disease or injury associated with unilateral affection by a geriatrician. Criteria for inclusion and exclusion are further described in Table 3. The number of included controls differ in **Paper I** (n=57) and **Paper II** (n=56) due to the differences in an inclusion criterion related to gait velocity (Table 3). In both Papers, mean age of included controls were 77 SD 5 years (70% female in Paper I, 71% female in Paper II).

Table 3: Inclusion and exclusion criteria, outcome measures and symmetry indices in Papers I - III

Paper	Inclusion criteria	Exclusion criteria	Outcome measures	Symmetry indices (SI)[1]
I	*Patients (Sample I):* • Age 30 – 70 years • First stroke within 2-6 years earlier • Home dwelling and medically stable • Able to walk 10m without personal assistance other than ankle-foot orthoses *Controls (Sample III):* • Convenience sample waiting for cataract surgery • Able to walk at least 1.5 mile without difficulties	*Patients:* • Severe communication, cognitive or perceptual difficulties • Disabling pain of the lower limbs *Controls:* • Previous cerebral infarction • Other disease or orthopedic injury associated with one-sided affection	*Patients and Controls* • AP, V and ML trunk movement symmetry assessed by triaxial trunk accelerometry (Logger technology, HB, Malmö, Sweden) • SS and SL symmetry assessed by electronic walkway (GAITRite® Gold, CIR Systems Inc. NJ, USA)	*Patients:* $SI_{footfall}$: Formula 1a *Controls:* $SI_{footfall}$: Formula 1c *Patients and Controls:* SI_{trunk}: Formula 6 *Perfect symmetry equals:* $SI_{trunk} = 0.0$ $SI_{footfall} = 1.0$
II	*Patients (Sample II):* • Primary hip OA and scheduled for hip replacement surgery at selected hospitals • Geographic home location within the Oslo or Bergen area, or willing to travel to test location	*Patients:* • Musculoskeletal ailments likely to influence walking ability other than primary hip osteoarthroses • Gait velocity of .9 m/s not within the range of gait velocities at all test	*Patients and Controls* • AP, V and ML trunk movement symmetry assessed by triaxial trunk accelerometry (Logger technology, HB, Malmö, Sweden) • SS and SL symmetry assessed by electronic walkway (GAITRite® Gold, CIR Systems Inc. NJ, USA)	*Patients and Controls:* $SI_{footfall}$: Formula 2 SI_{trunk}: Formula 6 *Perfect symmetry equals:* $SI_{trunk} = 0.0$ $SI_{footfall} = 1.0$

	• Able to walk 10 meters without assistive devices *Controls (Sample III):* • Convenience sample waiting for cataract surgery • Able to walk at least 1.5 mile without difficulties	occasions *Controls:* • Previous cerebral infarction. Disease or orthopedic injury associated with one-sided affection • Gait velocity of .9 m/s not within the range of gait velocities at all test occasions		
III	*Patients (Sample II)* : • Geographic home location within the Oslo or Bergen area or willing to travel to test location • Able to walk 10 meters without assistive devices.	*Patients:* • Missed more than one test occasion. • Gait velocity of .9 m/s not within the range of gait velocities at all test occasions • Postoperative complications	*Patients:* • AP, V and ML trunk movement symmetry assessed by triaxial trunk accelerometry (Logger technology, HB, Malmö, Sweden) • SS and SL symmetry assessed by electronic walkway (GAITRite® Gold, CIR Systems Inc. NJ, USA) • Preferred and fast gait velocity • Self-reported function assessed by The Hip disability and Osteoarthritis Outcome Score questionnaire (HOOS), version 1.1	*Patients and Controls:* $SI_{footfall}$: Formula 2 SI_{trunk}: Formula 6 *Perfect symmetry equals:* $SI_{trunk} = 0.0$ $SI_{footfall} = 1.0$

[1] For equations used to calculate symmetry indices, see Table 2.

Table 4: Diagnostic group based on radiographic images of Sample II, osteoarthritis patients (**Papers II** and **III**). Total hip replacement prosthesis (acetabulum/femur components), operating approach and postoperative weight bearing restrictions (PWB[1] and WBAT[2]) in **Paper III**.

		Paper III n=34			Paper II (n=37)
		PWB[1] n(%)	WBAT[2] n(%)	Total n(%)	n(%)
Diagnostic group	Unilateral osteoarthritis	5 (15)	11 (32)	16 (47)	16 (43)
	Bilateral osteoarthritis 1st hip to be operated	4 (12)	5 (15)	9 (26)	10 (27)
	Bilateral osteoarthritis 2nd hip to be operated	6 (18)	3 (9)	9 (26)	11 (30)
Prosthesis/ Approach	Charnley Ogee cement / Charnley cement Direct lateral approach	2 (6)	12 (35)	14 (41)	
	Reflection cement / Spectron cement Direct lateral approach	5 (15)	3 (9)	8 (24)	
	Reflection / Landos Corail cement less Direct lateral approach (n=3) Dorsal approach (n=1)	5 (15)		5 (15)	
	Other brands. Direct lateral approach	3 (9)	1 (3)	4 (12)	
	Birmingham hip resurfacing. Dorsal approach		3 (9)	3 (9)	

[1]PWB = Partial weight bearing. Patients were instructed to allow a maximum load of 20-30 kg on the operated leg and to use crutches three months post operatively. Patients operated with direct lateral approach were additionally instructed to avoid active hip abduction exercises six weeks post operatively.
[2]WBAT = Weight bearing as tolerated, limited by pain. Patients were instructed to use crutches six weeks post operatively.

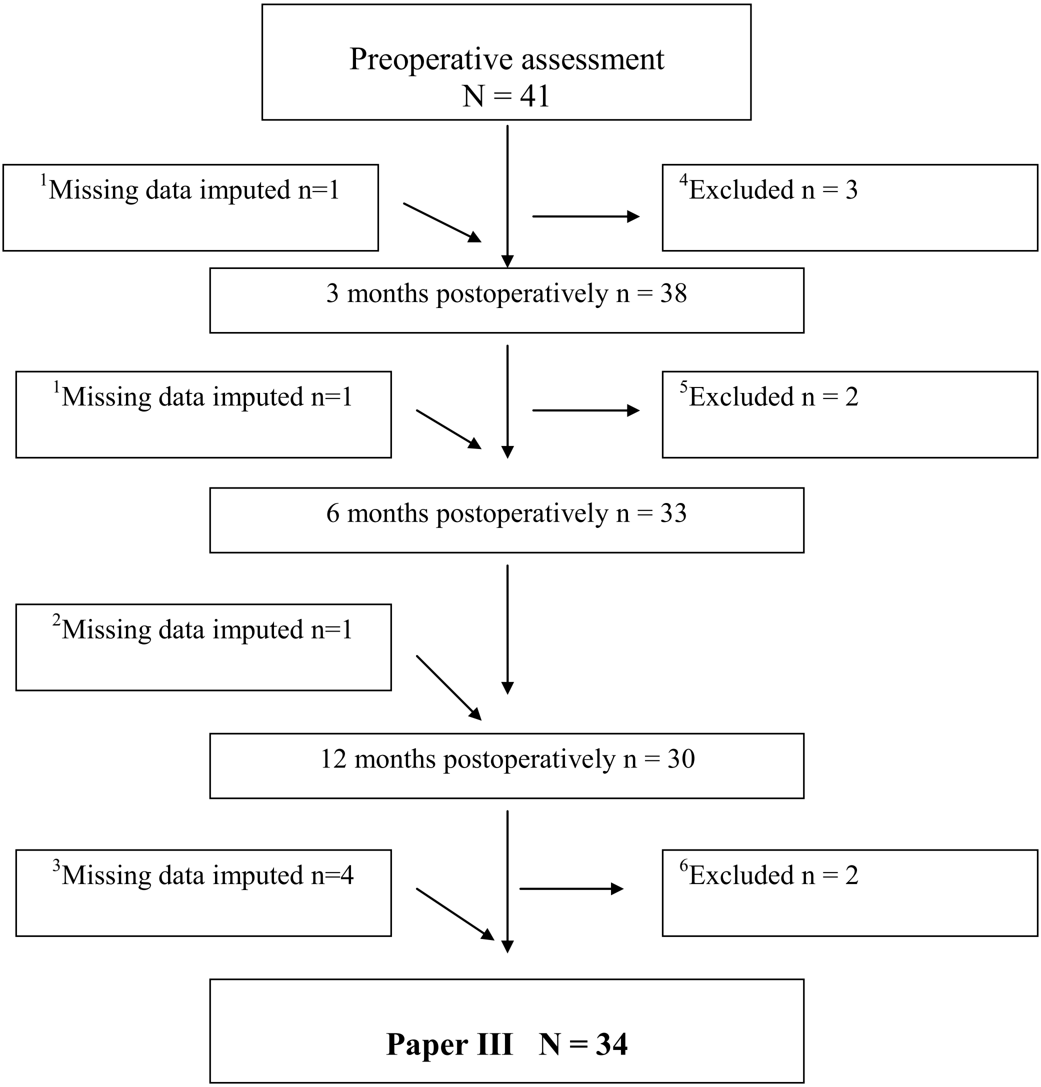

Figure 3.Flowchart for osteoarthritis patients (Sample II), indicating excluded and imputed data at preoperative, 3, 6 and 12 months test occasions (**Paper III**)

[1]Missing data imputed: Electronic walkway malfunctioning n=1
[2]Missing data imputed: Patient unable to attend n=1
[3]Missing data imputed: Accelerometer malfunctioning n = 1, Unable to attend n= 3
[4]Excluded: Postponed surgery n = 1, Postoperative complications n = 2
[5]Excluded: Did not meet requirements of 0.9m/s for gait velocity n=2
[6]Excluded: Unable to attend 2 test occasions n = 2

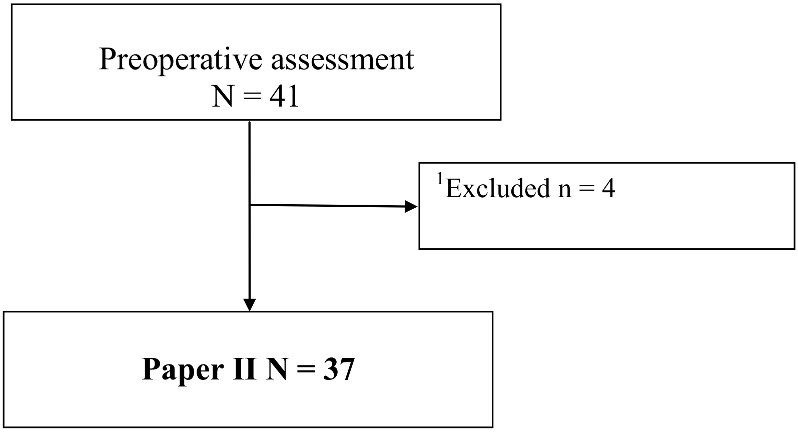

Figure 2. Flowchart for osteoarthritis patients (Sample II), preoperative assessment (**Paper II**)
[1]Excluded: Postponed surgery n = 1, Postoperative complications n = 2, Equipment malfunctioning n = 1

3.3 Outcome measures

Objectively assessed gait symmetry is the primary outcome measure throughout this thesis (**Papers I-III**). Symmetry in the AP, V and ML direction of trunk movement (trunk symmetry) is assessed by a triaxial trunk accelerometer (Logger technology, HB, Malmö, Sweden), while step length and single support symmetry (footfall symmetry) is assessed by an electronic walkway (GAITRite® Gold, CIR Systems Inc.NJ, USA). In **Paper III**, outcome measures additionally include gait velocity assessed by the electronic walkway and self-reported function assessed by Hip disability and osteoarthritis outcome score questionnaire (HOOS). Measures of gait velocity and HOOS do not provide information regarding gait symmetry. However, gait velocity is considered a fundamental measure of gait (Perry, 1992), while self-reported function is important because patient satisfaction after clinical interventions also leads to better compliance throughout rehabilitation (Brokelman et al., 2008).

Measures of gait velocity and self-reported function are easily administered and frequently used by clinicians for postoperative evaluation of patients (Brokelman et al., 2008, Nilsdotter et al., 2003, van den Akker-Scheek et al., 2007). The measures were included to provide information regarding time and magnitude of postoperative change in these measures in relation to gait symmetry.

3.3.1 Trunk movement symmetry (Papers I-III)

Trunk movement symmetry was assessed in AP, V and ML direction of movement during gait by an accelerometer connected to a portable data logger. An accelerometer is a force transducer that measures acceleration, the reaction forces, associated with a given rate of change in velocity (Moe-Nilssen, 1999), as described by Newton's 2nd law (acceleration = force/mass). The triaxial piezoresistant accelerometer has a weight of 0.015 kg and provides stable steady state response, little drift (Moe-Nilssen, 1998a), reliable and valid measures of movement during gait (Hodt-Billington et al., 2010, Henriksen et al., 2004, Moe-Nilssen, 1998c), also during rehabilitation after THR (Henriksen et al., 2004, Moe-Nilssen, 1998c, Hodt-Billington et al., 2010, Hodt-Billington et al., 2010, Aminian et al., 1999). To avoid unwanted drift between sessions, the device was routinely auto calibrated before every test session. Accelerometers are increasingly used to evaluate balance and symmetry during gait (Aminian et al., 1999, Menz et al., 2003a, Moe-Nilssen and Helbostad, 2004, Hodt-Billington et al., 2008).

The accelerometer was secured in a customized belt and placed at the L3-level of the spine. Rotation at this position is low during gait, hence rotational motion is reduced and will not contaminate the linear accelerometer output, but as intended reflects actual lower trunk acceleration during movement (Kavanagh and Menz, 2008). A computerized stopwatch was synchronized to the accelerometer and registered time sequences for each walk through photoelectric cells. Data were stored on Personal Computer Memory Card International Association (PCMCIA) data cards (Logger technology HB, Malmö, Sweden) worn in a separate belt around the subject's waist, and subsequently transferred to a computer for offline processing. Analogue signals were low-pass filtered at 55 Hz and sampled at 128 Hz before digitalized signals were processed and analyzed in Matlab 7 (The Mathworks Inc., Natick, MA, USA).Trunk acceleration amplitudes for each walking trial were expressed by root mean square (RMS) values (Moe-Nilssen, 1998b, Helbostad et al., 2007). Acceleration signals were transformed to a true horizontal–vertical Cartesian coordinate system keeping the AP axis in the sagittal plane to avoid unwanted gravity components caused by inaccuracy in the positioning of the sensor, tilting of the sensor due to the curvature of the lumbar spine, or forward leaning of the trunk. The transformation procedure applies the accelerometer as a inclinometer, utilizing the gravity component of the acceleration signal to calculate and eliminate tilts (Moe-Nilssen, 1998a, Moe-Nilssen, 1999).

Trunk acceleration amplitudes for each walking trial were expressed by root mean square (RMS) values. Trunk acceleration regularity (between-stride and between-step regularity) was expressed by an autocorrelation procedure, as described by Moe-Nilssen and Helbostad (2004) and adopted by other investigators (Tura et al., 2010). The unbiased autocorrelation function Ad(m) of the sample sequence x(i) was:

$$Ad(m) = \frac{1}{N - |m|} \sum_{i=1}^{N-|m|} x(i) \cdot x(i+m)$$

N is the number of samples and m is the time lag expressed as number of samples. Ad(m) is computed on AP, V and ML acceleration signals separately during the middle 4.2 meters of every 7-meter gait sequence. A perfect replication of the gait cycle signal between neighboring steps or strides will return an autocorrelation coefficient of $|1|$, and no association a coefficient of 0, indicating that the higher the absolute value of the autocorrelation coefficient, the higher between-step or between-stride regularity. Because ML movements of neighboring steps are in opposite phase, ML between-step trunk regularity is displayed in negative values. Therefore absolute values are used in the calculation of SI indices.

Symmetry indices (SI_{trunk}) were calculated separately for each of the AP, V and ML measures by formula 6 (Table 2) in this thesis:

$$SI_{trunk} = \text{Between-tride regularity-}|\text{Between-step regularity}|$$

3.3.2 Footfall symmetry (Papers I-III)

Symmetry in single support (% of stride time) and step length (meter) were registered by the GAITRite® electronic walkway. The GAITRite is a transportable roll up carpet with an active area of 0.61 meters wide and 4.26 meters long and contains approximately 13800 pressure sensitive sensors that register footprint position during gait. Data are collected while the patients move unrestricted across the walkway and immediately displayed on a computer connected to the electronic carpet. The walkway provides reliability and valid measures of temporal-spatial gait parameters (Webster et al., 2005, Bilney et al., 2003, Menz et al., 2004, van Uden and Besser, 2004). In **Paper I**, the GAITRite34sg software was used to calculate symmetry measures, while the GAITRite3A software was used in **Papers II** and **III**. By default, the software defines the beginning of each step from the time of heel contact. However, in **Paper I**, a toe-to-toe function was used for subjects who were ‘‘toe-walkers’’.

3.3.3 Gait velocity (Paper III)

Gait velocity was registered by the electronic walkway at all test occasions, and evaluated as an outcome measure in **Paper III** and as descriptive information in **Papers I** and **II**. Gait velocity describes a person’s rate of travel, or the time required to cover a designated distance (Perry, 1992). Preferred gait velocity is defined as the spontaneous rate of travel utilizing the optimum functional balance of the person’s physical qualities (Perry, 1992). Gait velocity is mainly determined by and highly related to stride length and cadence (Menz et al., 2003b). Older subjects often walk with shorter steps and lower cadence, hence slower velocity compared to younger subjects (Menz et al., 2003b, Lusardi et al., 2003). This may be a compensatory strategy to maintain balance due to age-related deficits in physiological functions such as reduced strength in the lower limbs (Menz et al., 2003b).

3.3.4 Self-reported function (Paper III)

It has been suggested that self-reports should serve as gold standard in functional assessment of musculoskeletal conditions were the patient's perspective and health-related quality of life are of high interest (Patrick et al., 2007). The HOOS questionnaire, version 1.1, is disease specific and developed to evaluate self-reported problems of patients with hip disabilities with or without hip OA (Nilsdotter et al., 2003, de Groot et al., 2007). HOOS has adequate measurement properties of validity, reliability and sensitivity to change, and is recommended for use in the evaluation of patients with hip OA before and after THR. HOOS includes all questions of the more frequently used Western Ontario and McMaster University osteoarthritis index (WOMAC) questionnaire, meant to facilitate comparison of outcome assessed using the two questionnaires. HOOS has reduced floor effect compared to WOMAC due to additional measures of new dimensions of symptoms included in the questionnaire (Klassbo et al., 2003). HOOS contains five subscales with a total of thirty-nine items:

P = Pain (9 items)
S = Other symptoms, including stiffness (5 items)
ADL = Function in daily living (17 items)
QOL = Hip-related quality of life (4 items)
SP = Function in sport and recreation (4 items)

Data from the SP subscale was not registered at postoperative tests due to postoperative movement restrictions. Each item is given a score from 0 (no symptoms) to 4 (extreme symptoms), and further scoring is done according to the "HOOS LK 1.1 User's Guide" (HOOS, 2003). In each subscale, no symptoms equal a score of 0, while 100 indicates extreme symptoms (HOOS, 2003).

Questionnaires were posted to each patient less than one week before test occasion and returned when subjects arrived at test occasions. A manual control was done by the examiner to ascertain reply to all items in the questionnaire.

3.4 Protocol

To enhance reproducibility and ease comparison across studies, it is a goal that data collection should follow similar protocols across studies (Kressig and Beauchet, 2006). Data collection for this thesis was performed at five different test locations, hence the attention given to a reproducible protocol was highlighted. Data collection was performed as suggested in the *Guideline for Clinical Application of spatio-temporal Gait Analysis* in Older Adults (Kressig and Beauchet, 2006). Hence, every gait analysis took place in a well-lit environment, in a closed hallway or in a gait laboratory without noise or visual distraction. Patients were informed to choose comfortable and non-restrictive clothes and low-healed footwear. In Paper III, the choice of footwear was recorded at the first gait evaluation, and patients were reminded of their choice and asked to wear the same pair at postoperative tests. For safety precautions, the edge of the electronic walkway was fixed to the floor with duct tape. All tests were performed at steady state self-selected gait velocities after standardized walking instructions. The following instructions were given to the patients: 1) “Walk more slowly than your preferred speed”, 2) “Walk at your preferred speed”, and 3) “Walk as fast as you can safely do without running”. Each instruction was followed by; “go back and forth once”. Each gait evaluation took approximately 15 minutes, including oral instructions prior to the tests and combined oral and visual feedback on footfall symmetry measures registered by the electronic walkway after the test.

3.5 Statistical analysis

Papers I-III: Demographics are presented as mean with standard deviations (SD). Symmetry measures were checked for speed dependency using data from the six walks performed at different speed by each subject. First, the gradients (b_1) of individual linear trend lines of a symmetry measure versus walking speed were tested by one-sampled t-tests for $H_0{:}b_1=0$. In **Papers II and III**, a linear relation to walking speed was demonstrated, hence it was warranted to control for gait velocity. In **Paper I**, no linear relation was found, and an additional check for the possibilities of a curvilinear relationship was performed by testing the second degree coefficients (b_2) of individual quadratic trend lines by one-sample t-tests for $H_0{:}b_2=0$. No curvilinear relationship was found, hence controlling for gait velocity in **Paper I** was not warranted. Spearman's rho analyses were performed to evaluate associations between outcome measures. Results are displayed in chapter 4.4(unpublished results). Statistical analysis were done in Microsoft Excel 2003 and Statistical Package for Social Sciences (SPSS) version 13 and 15, and level of significance was set at $p<.05$, unless stated otherwise (Paper III).

Paper I: Independent samples t-tests were used to test between group differences in anthropometric data. Reliability of the symmetry measures are evaluated with Intraclass correlation coefficient (ICC 3.1) two-way mixed models (consistency) which ignores the presence of systematic errors in the analyzed data. Outcome measures were presented as mean with standard error (SE). Paired samples t-tests were used to assess differences between limbs in footfall measures. Multiple linear regression analyses were performed to investigate the relationship between gait measures in the two groups, while ROC was used for additional discriminating analyses.

Paper II: Outcome measures were presented as mean with confidence intervals (CI). One-way analysis of variance (ANOVA) was used to test for possible differences in outcome measures related to differences in hip involvement in patients with OA. Between-group differences in gait velocity and symmetry measures were tested by independent samples t-tests, while analysis of covariance (ANCOVA) was performed to further investigate between-group differences in symmetry and gait velocity. Covariates were included in the final analysis when appropriate. Optimal cut-off were decided through receiver operating characteristic curves (ROC) and the classification ability of these cut-offs were compared to the classification ability of the 10 % criterion (cut-off).

Paper III: Paired sampled t-test was used to evaluate change in patients body height, body weight, body mass index and the total number of steps used to calculate outcome measures at each test occasion (step count), from preoperative to 12 months postoperative assessments. Outcome measures were presented as median with 25th and 75th percentiles. Wilcoxen rank-sum test was used to assess possible differences in outcome measures related to dichotomous covariates, while the Kruskal-Wallis test, followed by Wilcoxen rank sum test when appropriate, was used to assess differences in outcome measures related to hip involvement. Repeated measures analyses were done with the Friedman's ANOVA, while the Wilcoxen signed rank was used to assess changes between neighboring assessments. To correct for the number of tests in the Wilcoxen signed-rank analysis, the Bonferroni corrections (α/number of comparisons) was used to decide a critical value (Field, 2009). Effect size (ES) was used to report changes in outcome measures between neighboring test occasions, and between preoperative and 12 months postoperative tests (Rosenthal, 1991).

Unpublished results (Table 5-8): Spearman's rho correlation analysis of symmetry measures, gait velocities (**Papers I-III**), and HOOS sub scales (**Paper III**) were performed to evaluate associations between outcome measures within each patient group and within the control group. Revised receiver operating characteristic curves (ROC) calculations of footfall symmetry indices (**Paper I)** were performed to evaluate potential differences in discriminating ability of step length and single support symmetry when symmetry indices are calculated based on formula 2 (**unpublished results**) or formula 1a/b (**Paper I**).

3.6 Controlling for gait velocity

Many outcome measures may change with walking speed, and it is well established that step length and cadence are highly related to gait velocity (Eppeland et al., 2009, Winter DA., 1991, Fransen M et al., 1994, Kirtley, 2006), but also body acceleration is found to be influenced by gait velocity (Kavanagh et al., 2006, Moe-Nilssen, 1998b, Menz et al., 2003a). Whether measures of step length symmetry and other symmetry measures are related to walking speed is not as obvious, hence design of studies addressing gait symmetry should involve considerations related to differences in gait velocity. In *Guidelines for Clinical Applications of Gait Analysis in older adults* (Kressig and Beauchet*,* 2006*),* the authors suggest that procedures for gait analysis should involve data collection at three different walking speeds, ranging from slow to fast. The procedures used in this thesis followed these recommendations (Kressig and Beauchet, 2006). In **Paper I**, statistical analysis showed no relation between gait velocity and gait symmetry in neither sample, hence there was no need to control for the effect of speed. Data used in analysis are therefore based on mean values from all six walks (**Paper I**). In **Papers II and III**, a relationship between gait velocity and gait symmetry was found in the OA sample, hence controlling for the effect of speed was required to distinguish differences in gait abnormality from the effect of differing walking speeds (Marigold and Patla, 2008, Helbostad and Moe-Nilssen, 2003, Eppeland et al., 2009). Based on the six walking trials, individual linear trend lines were calculated for each symmetry measure, over the speed range demonstrated by that subject. From the individual linear trend lines, point estimates at a common speed could be used for analysis between subjects and between test-occasions, even if actual walking speeds differed between patients and test occasions. A common speed of 0.9 m/s was chosen as reference speed, as it was within the range of gait velocities for all subjects (Figure 4).

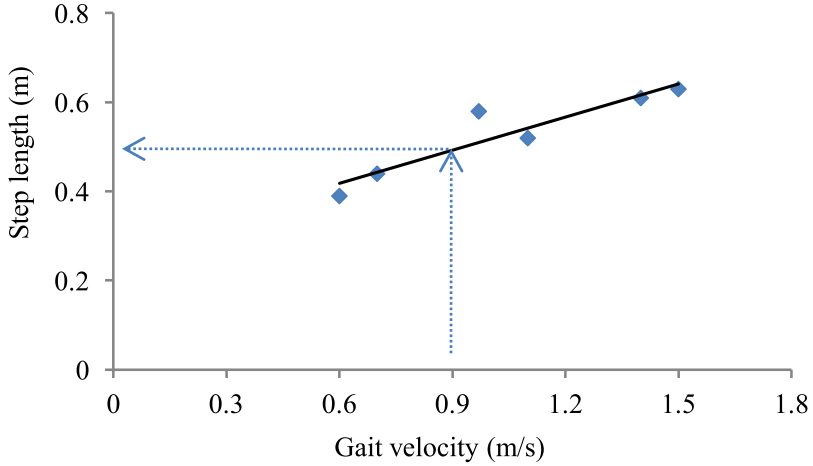

Figure 4: Estimation of step length at 0.9 m/s for a typical subject when controlling for gait velocity. The squares represent actual step length at the six walks performed by the subject.

4. Review and synopsis of papers

4.1 Paper I:

Should trunk movement or footfall parameters quantify gait asymmetry in chronic stroke patients?

Hodt-Billington C, Helbostad JL, Moe-Nilssen R

Gait & Posture 2008:27: 552-8

Objective: To investigate discriminative ability of gait symmetry measures in chronic stroke patients in relation to controls, and to identify gait symmetry measures with the best ability to discriminate between the two groups.

Methods: A group of chronic stroke patients (n=20) and a group of controls (n=57) walked six times along a 7-meter walkway at slow, preferred and fast speed. Measures of AP, V and ML trunk symmetry were assessed using triaxial accelerometry. Simultaneous assessment of SS and SL symmetry was based upon data from an electronic walkway. Symmetry measures were first evaluated for reliability on the chronic stroke patients (Sample I) who repeated the test procedure for 2 walks at slow, preferred and fast walks (totaling 6 walks) three times. Discriminative ability was evaluated using ROC analysis.

Results: Controlling symmetry measures for gait velocity was not warranted as data showed no relation to walking speed. To increase power, symmetry data were calculated from mean values of the six walks. Reliability of all symmetry measures was acceptable to excellent with ICC (3.1) of .74 for SL symmetry and above .84 for all other symmetry measures. Discriminating ability was significant for trunk symmetry measures, but not for footfall measures.

Conclusion: Trunk and footfall symmetry measures are reliable and may be used in evaluation of gait measures. Only trunk symmetry measures showed the ability to discriminate the two groups based on gait symmetry.

4.2 Paper II

Criteria of gait asymmetry in patients with hip osteoarthritis

Hodt-Billington C, Helbostad JL, Vervaat W, Rognsvåg T, Moe-Nilssen R

Physiotherapy Theory and Practice 2011:Early Online 1-8:

DOI:10.3109/09593985.2011.574783

Objective: To investigate discriminating abilities of trunk and footfall gait symmetry measures in patients with hip OA and controls. To assess if a 10% cut-off value is valid as a general criterion of pathologic gait asymmetry across measures.

Methods: AP, V and ML trunk symmetry, SS and SL symmetry were assessed simultaneously by trunk accelerometry and an electronic walkway in OA patients (n=37) and controls (n=56). Subjects walked six times along a 7-meter walkway at slow, preferred and fast speed, before data were evaluated using ROC analysis, at point estimates calculated for a common gait velocity of 0.9 m/s.

Results: AP, V and SS symmetry measures showed best discriminative abilities. The general 10% criterion of gait asymmetry and optimal cutoff criteria calculated for each symmetry measure showed approximately equal total classification ability. However, the optimal cutoff criteria classified a high number of controls as having pathological gait asymmetry.

Conclusion: The general criterion of 10% is valid with high total classification ability, does not classify asymmetry in able-bodied subjects as pathological, and is feasible for use on individual patients in the clinic as well as in research.

4.3 Paper III

Changes in gait symmetry, gait velocity and self-reported function following total hip replacement

Hodt-Billington C, Helbostad JL, Vervaat W, Rognsvåg T, Moe-Nilssen R

Journal of Rehabilitation Medicine 2011: 43 (9): 787-93

Objective: To investigate the magnitude of change of gait symmetry, gait velocity and self-reported function at different time-points during the first 12-months after THR.

Methods: AP, V and ML trunk symmetry, SS, SL symmetry and gait velocity were assessed simultaneously by trunk accelerometry and an electronic walkway in OA patients (n=34). Subjects walked six times along a 7-meter walkway at slow, preferred and fast speed. Self-reported function was assessed by HOOS. Gait symmetry data were normalized for gait velocity and analyzed at a common speed of 0.9 m/s. Changes between test occasions were reported as unit-less ES.

Results: All measures showed ES >.30 from preoperative to 12 months postoperative assessments, and improvements were significant (p<.05) in all measures, except ML symmetry. In general, gait symmetry and gait velocity improved most 6 and 12 months postoperatively, while self-reported function improved most 3 months postoperatively.

Conclusion: Early improvement was seen in self-reported function, suggesting immediate relief from stiffness and pain, while gait symmetry and velocity improved later postoperatively, suggesting that gait quality and performance may benefit from prolonged rehabilitation.

4.4 Unpublished results

1) **Association between outcome measures in the hemiplegic group (Paper I symmetry formula 2), the controls (Paper II) and in preoperative assessment of OA patients (Paper III)**
2) **Revised calculations of discriminative ability of single support and step length in Paper I (symmetry formula 2)**

Objective: The first aim was to investigate within group associations between outcome measures in **Paper I-III**. The second aim was to evaluate revised calculation of discriminative ability of symmetry measures (**Paper I**) when gait symmetry was based on symmetry formula 2 (Table 2) rather than symmetry formula 1a/b (**Paper I**).
*Methods:*1) Spearman's rho correlations were calculated from outcome measures within each sample in **Papers I-II** and in **Paper III** preoperative data. 2) Discriminative ability of step length and single support symmetry based on symmetry formula 2 (Table 2) were calculated through ROC analysis (**Paper I**).
*Results:*1) In **Papers I-II** (Tables 5-6) and in preoperative data **Paper III** (Table 7), fast and preferred gait velocities were significantly associated (r=0.81-0.87). Associations between AP, V and ML trunk symmetry measures were also highly significant within each patient group (r=0.64-0.83), and in controls (r=0.34-0.52). Low associations were seen between footfall symmetry and other outcomes, except between trunk and single support symmetry preoperatively (r=0.62-0.73) (**Paper III**). Association between HOOS sub-scales in the OA group (**Paper III**) were mostly significant with r< 0.57. 2) Revised calculations of discriminating ability of symmetry measures (**Paper I**) calculated based on formula 2, Table 2 left conclusions unchanged (Table 8). Hence step length and single support symmetry measures did not show the ability to discriminate gait in controls from gait in patients post stroke.

Table 5: Spearman's rho correlations of measures in the hemiplegic group[1] (Sample I).

		Velocity	Symmetry measure				
		Fast	AP	V	ML	SL	SS
Velocity	Preferred	.87**	-.46*	-.08	-.33	.15	.07
	Fast		-.59*	-.32	-.48*	.27	.17
Symmetry measure	AP			.64*	.80**	-.17	.07
	V				.66*	-.49*	.01
	ML					-.25	.03
	SL						-.13

[1]SS and SL symmetry calculations based on low limb versus high limb values (formula 2, Table 2).
Abbreviations: AP: anteroposterior, V: vertical, ML: mediolateral, SL: step length, SS: single support.

Table 6: Spearman's rho correlations of measures in controls[1] (Sample III).

		Velocity	Symmetry measure				
		Fast	AP	V	ML	SL	SS
Velocity	Preferred	.85**	-.08	-.14	-.07	.08	.00
	Fast		-.07	-.18	-.08	.07	-.06
Symmetry measure	AP			.48**	.34*	.31*	-.06
	V				.52*	.04	.14
	ML					-.13	.34*
	SL						-.00

[1]SS and SL symmetry calculations based on low limb versus high limb values (formula 2, Table 2).
Abbreviations: AP: anteroposterior, V: vertical, ML: mediolateral, SL: step length, SS: single support.

Table 7: Spearman's rho correlations between outcome measures in patients with hip osteoarthritis (Sample II). Preoperative test occasion.

		Velocity	Symmetry measure					HOOS				
		Fast	AP	V	ML	SL	SS	P	S	ADL	QOL	SP
Velocity	Preferred	.81**	-.42*	-.30	-.44*	-.29	-.35*	-.25	-.10	-.03	-.11	-.04
	Fast		-.47*	-.26	-.42*	-.27	-.33*	-.10	.01	.01	.10	.03
Symmetry measure	AP			.83**	.80**	.38*	.73**	.08	.19	.04	.12	.08
	V				.71**	.28	.62**	-.04	.20	.08	.25	.05
	ML					.40*	.72**	.08	.21	.01	.22	.14
	SL						.22	.10	.25	.02	.24	-.07
	SS							.15	.14	-.05	.16	.17
HOOS	P								.29	.47*	.32	.40*
	S									.44*	.37*	.37*
	ADL										.57**	.44*
	QOL											.38*

Abbreviations: HOOS: Hip disability and osteoarthritis outcome score questionnaire, AP: anteroposterior, V: vertical, ML: mediolateral, SL: step length, SS: single support, P:pain, S:other symptoms including stiffness, ADL: function in daily living, QOL: hip related quality of life, SP: function in sport and recreation.

Table 8: Receiver Operator curve analysis (ROC) of gait symmetry measures (SI) with area under the curve (AUC), standard error (SE) and significance values (p-values). Analysis involve patients with hemiplegic gait compared to controls (**Paper I**).

SI	Formula no	AUC	SE	p-value
AP	6[1]	.82	.06	<.001
V		.90	.03	<.001
ML		.76	.07	.001
SL	2[2]	.58	.08	.32
	1a/c[3]	.53	.08	.70
SS	2	.58	.07	.28
	1a/c	.62	.08	.10

[1] SI_{trunk}= Between stride regularity – │Between step regularity│

[2] $SI_{footfall}$=│1 –Limb with lower value/Limb with higher value│

[3] $SI_{footfall}$= Controls: │1 – Left limb/Right limb│
Hemiplegic group: │1 – Unaffected limb/Affected limb│

5. DISCUSSION

The overall aim of this thesis was to evaluate measures of gait symmetry in subjects with disease or injury related to one-sided affection. This thesis also aims to relate objective measures of gait quality (gait symmetry) to other more frequently used measures of function (gait velocity) and self-reported function in patients with disease or injury resulting in asymmetric gait. Although often considered incompatible, this thesis also aims to emphasize how methodological and clinical perspectives and demands related to objective measurements and clinical applicability may be united.

5.1 Methodological considerations

A cross-sectional design was chosen in **Papers I and II**, as this design is suited to investigate classification ability and cut-off criteria of outcome measures. The cross-sectional study design allows data to be collected at a defined time, but does not give information regarding cause and/or effect (Field, 2009). In **Paper II**, a cut-off value of 10% gait symmetry is proposed to separate pathologic gait asymmetry from normal gait asymmetry. Even though continuous scales may be more exact and therefore a preferential choice if possible, categorization of data may be useful for screening or decisions regarding whether or not a patient needs intervention (Streiner and Norman, 2008). The ROC curve represents an objective approach to data analysis for such classification.

In **Paper III**, a prospective long-term repeated measures design was chosen to evaluate postoperative change in outcome measures. Repeated measures designs have more power to detect effects than independent measures designs, because the repeated tests will lower the possibilities of unsystematic variation caused by other sources than those intended by the researcher (Field, 2009). Hence, within-participant variance will be a result of the effect of the manipulation (THR) and individual differences in performance (Field, 2009). Power remains high with a lower number of included participants. Difficulties in repeated measures designs involve that results from one subject may be missing at one or more test occasions, due to circumstances unrelated to the outcome of interest (Davis, 2002). However, Streiner and Norman (Streiner and Norman, 2008) considers validity of the results to be unaffected when missing and replaced items is limited to 5 percent or less (Streiner and Norman, 2008). In **Paper III**, only 6 out of 156 items (3.8%) were imputed after loss to follow up in trunk symmetry measures, while 8 (5.1%) items were lost to follow up in SL and SS symmetry measures. In conclusion the follow up rate in **Paper III** was high.

ES was chosen to describe the magnitude of change in **Paper III** as it is suited to compare the magnitude of change in measures using different scales and units of measurements (Kazis et al., 1989, Norman and Streiner, 2000). However, no consensus exists as to how much change that is necessary for change to be considered clinically important (Streiner and Norman, 2008). The frequently used Minimal Clinically Important Difference (MCID) is limited to reflect functional change, and does not reflect whether function remains pathologic or becomes normal (Tubach et al., 2005). There are suggestions that the minimally important difference (MID) equaling Cohen's moderate effect size of 0.5, or improvement visible to the eye, should be considered enough change (Cohen, 1992). In the literature, 0.5 has also been referred to as a large effect (Field, 2009). As further discussed in chapter 5.5, only V and not AP, ML, SS and SS symmetry, but all HOOS sub-scales and gait velocity measures showed ES>0.5.

When assessing change one should also consider the possibilities of floor or ceiling effects, which may be present if >15% of the respondents achieve the highest or lowest possible score despite adequate design and methods (Terwee et al., 2007). None of the outcome measures used in this thesis showed such signs of floor or ceiling effect. However, conflicting results regarding potential ceiling effects of the HOOS questionnaire have previously been reported (Nilsdotter et al., 2003, de Groot et al., 2007).

5.2 Samples

Subjects included in this thesis comprised 20 subjects with hemiplegia, mean age 58 SD 8 years (**Paper I**), 37 subjects with end-stage hip OA, mean age 63 SD 10 years (**Paper II**), and 34 subjects with hip OA before and after hip replacement surgery, mean age 63 SD 11 years (**Paper III**). The subjects included in **Papers II and III** originate from the same sample, excluding patients lost to follow up in **Paper III**. Controls consist of 57 and 56 subjects (mean age 77 SD 5 years) in respectively **Papers I and II**. The controls were a convenience sample of subjects waiting for cataract surgery. Criteria for inclusion and exclusion are strict (Table 3), and included subjects did not report any gait difficulties and were able to walk at least 1.5 mile without difficulties. They were further assessed by a geriatrician and were cleared of any previous cerebral infarction, or any other disease or orthopedic injury associated with one-sided affection. Although otherwise healthy and without known unilateral involvement, they may have had altered gait characteristics unknown to the authors. Controls were significantly older than both patient groups, and this may have affected the results, but loss of function caused by disease is most often of greater magnitude and superimposed on loss of function caused by age alone (Wolfson, 2001). Also, In contrast to the frequently reported age and gender related differences in step length and gait velocity (Senden et al., 2009), such age and gender related differences are not reported for gait symmetry (Senden et al., 2009), further justifying the choice of controls. Ethical, economical, and methodological considerations also favor the reuse of controls when similar and standardized protocols for gait analysis are used, such as in this thesis.

5.3 Outcome measures

Objectively assessed trunk and footfall gait symmetry are the main outcome measures of this thesis, while objectively assessed gait velocity and subjectively assessed self-reported function are additional outcomes in **Paper III**. Measures used to assess gait and function in clinical rehabilitation should be easy to interpret and not take up too much of the patients' and clinician's time. It has been stated that the more elaborate the measurement system, the higher the cost, and the better the quality of the objective data (Whittle, 2007). In contrast to 3D camera systems which represent high quality, but also high costs, and time consuming assessment protocols, gait symmetry evaluations in this thesis were performed within 15 minutes, including oral instructions and information to the patients before and after the test. Difficulties in critically appraising outcome measures and interpreting results may limit the use of objective gait analysis in daily clinical practice. However, the methodology used in this thesis seems to have high feasibility and clinical applicability. The walkway's software provides opportunities for instant visual feedback and readily interpretable data reports. The software used in trunk symmetry evaluation in this thesis does not allow the same immediate feedback. However, improved software is recently developed and successfully applied (Aaslund et al., 2011), facilitating fast interpretation and improved opportunities for visual feedback and data reports on trunk symmetry measures.

5.3.1 Is one outcome measure enough?

One outcome measure would be the ideal choice in clinical gait evaluation. However, in **Papers I and III**, conclusions highlight the need to include several outcome measures to achieve a thorough clinical evaluation and disclose potential compensatory movement strategies. Preferred and fast gait velocities were highly associated (Tables 5-7) in **Papers I-III**, however further evaluation of sensitivity to change is needed before one may suggest the inclusion of only one of the two measures as necessary in a thorough gait evaluation. As demonstrated in **Paper I**, objective measures of gait symmetry demonstrated higher asymmetry for trunk movements compared to step length and single support asymmetry, suggesting compensatory movement strategies of the upper body. As also demonstrated in **Paper**

I, the chronic stroke patients with mild residuals of disabling symptoms from stroke, walked at high gait velocities (mean fast velocity: 1.56±.41 m/s) but with pronounced trunk asymmetry. As asymmetry in step length and single support were lower, this indicates the use of compensatory strategies of the upper body in an effort to increase gait velocity, hence increase functional performance. Olney and Richards (Olney and Richards, 1996) support these findings, but they also consider these compensatory strategies important and necessary to increase gait velocity or functional performance after stroke. Considering the negative side-effects of misalignment, such as higher loss of bone mass density and overuse injuries of unaffected joints and limbs (Jorgensen et al., 2000, Liu et al., 1999, Block and Shakoor, 2010, Shakoor et al., 2003, Shakoor et al., 2002, Patterson et al., 2008), there is a need for individually targeted long term interventions aiming to enhance gait velocity while remaining low degrees of compensatory strategies.

Among symmetry measures, AP, V and ML trunk symmetry showed significant relations within each sample in **Papers I-III**. This relation was lower in the controls ($r \leq 0.52$) than in the patients groups ($r \geq .64$), which may be explained by the low asymmetry (SI approaching 0) and low between-subject variance in gait symmetry seen in the controls. Within patient groups, the high association between trunk symmetry measures (Samples I and III), suggests a possibility to reduce the number of included measures required for a thorough gait analysis. However, this remains to be further investigated, in particular because the trunk symmetry measures displayed different patterns of postoperative change in **Paper III**. ML symmetry improvement was insignificant and seemed to occur at a later stage postoperatively compared to AP and V symmetry, suggesting a need for specific postoperative rehabilitation regimes, including strengthening of the abductor muscle group.

High gait velocity combined with high levels of trunk asymmetry and low association between the chosen outcome measures (Table 5-7, unpublished results), disfavor the possibility to include only one outcome measure when one aims to achieve a thorough gait evaluation. Compensatory strategies along with the selection of outcome measures best suited in evaluation of gait post stroke and in other patient groups need further investigation.

Self-reported function was included as a supplement to objective measures in **Paper III**, as also recommended by Lindemann et al (2006). The five sub-scales of the HOOS questionnaire were significantly associated. However, associations were relatively low (Spearman's rho <0.57) between all sub-scales, suggesting inclusion of all sub-scales in a thorough assessment. Postoperative improvement in self-reported function appeared earlier and with larger ES than improvement in the objectively assessed measures, as also previously supported (Kennedy et al., 2011). It has been argued that self-reported instruments may present superior results of validity and reproducibility compared to objective measures, and that it cannot be stated, by definition, that objective measures are better than subjective measures or the other way around (Poolman et al., 2009). In this thesis, the included instruments and measures are previously found valid and reliable (Bilney et al., 2003, Menz et al., 2004, van Uden and Besser, 2004, Webster et al., 2005, Henriksen et al., 2004, Thorborg et al., 2010, Moe-Nilssen, 1998c). Additional analysis of reliability of symmetry measures in Paper I, show acceptable to high reliability of all measures [ICC (3.1) of .84 to .90 for all measures, except for step length symmetry (ICC=.74)].

At preoperative test occasion, analysis of potential relationship between symmetry, gait velocity and self-reported measures (Table 7, unpublished results), showed most associations to be insignificant. The same lack of relationship was also found between most reported measures in additional analysis in **Paper I** (Table 5-6, unpublished results).

As such, these findings support the inclusion of all reported measures of gait symmetry of the upper body and footfall pattern, as well as one measure of gait velocity and all sub-scales of self-reported function for a thorough functional assessment after disease or injury causing one-sided affection.

5.3.2 Gait symmetry across patient groups

In **Papers I and II**, mean gait asymmetry and also discriminating abilities of symmetry measures were higher in patients with hip OA than in chronic stroke patients. This may reflect the difference in diseases, but also the different stages of the disease in which the patients are (OA disease about to receive THR, versus 2-6 years post stroke). Having a postoperative limp after THR is associated with unfulfilled expectations (Mancuso et al., 2009), and hip OA patients seem to experience continuous improvement in function post THR (Lavigne et al., 2010). Patients post strokes seem to follow a different pattern during rehabilitation, as they are likely to experience continuous functional improvement a few months post stroke (Jorgensen et al., 1995, Patterson et al., 2010a), before function may get worse (Patterson et al., 2010a) and remain lower 2-5 years post stroke (Muren et al., 2008, Patterson et al., 2010a). Disease dependent patterns of gait symmetry and recovery of gait symmetry needs further investigation that includes evaluation of primary and compensatory movement strategies.

5.3.3 Discriminating ability of trunk and footfall symmetry

In **Papers I-II**, measures of gait symmetry in the movement of the upper body showed better discriminating abilities than SL and SS symmetry measures. In SL and SS symmetry, discriminating ability was significant in **Paper II**, but not in **Paper I**. Hence SL and SS symmetry measures distinguished gait symmetry in controls from gait symmetry in patients with hip OA, but not in patients with chronic stroke. This difference may be partly explained by the lower number of hemiplegic patients compared to patients with hip OA. However, the difference is interesting because both groups of patients traditionally are believed to have high prevalence of lower limb asymmetry. The same group of controls was used in both papers, excluding the chance that the differences in discriminating ability should be affected by potential gait symmetry differences in controls. The ratio index was used to calculate SS and

SL symmetry, as advocated because it is valid and easily implemented and understood also in clinical settings (Patterson et al., 2010b). However, different calculations of SL and SS gait symmetry indices were chosen in **Papers I** and **II**, which may have affected the conclusions. In **Paper I**, symmetry indices were based on the left versus the right limb in the controls and the unaffected versus the affected limb in the patients (SI 1a and 1c, Table 2). Such symmetry indices based on limb affection, may even out potential differences in the direction of asymmetry when calculating group mean values. In **Paper II** (and **III**), symmetry indices are based on limb with lower values vs limb with higher values (SI 2, Table 2), which retains the magnitude in group mean values but eliminates the direction of asymmetry. Both ratio indices are previously used (Hesse et al., 2003, Madsen et al., 2004). Revised calculations of discriminating ability of symmetry measures in **Paper I**, using SI 2, instead of SI 1a/c, results in a 1% increase in mean SL asymmetry, while mean SS symmetry remains unchanged. Hence, conclusions on discriminative ability were unaffected by choice of SI (Table 8, unpublished). Discriminating ability of SL and SS symmetry in patients with chronic stroke and hip OA seem to differ. There is a need for further evaluation to confirm these findings.

As opposed to footfall symmetry measures, trunk movement symmetry measures showed high discriminative ability across **Papers I** and **II**, indicating that trunk symmetry measures appear to be efficient in the evaluation of gait asymmetry in hemiplegic and OA gait. The results from trunk symmetry evaluations are unaffected by the direction of gait symmetry, as data do not relate to specific limbs. Discriminative ability was high and consistent in **Papers I** and **II**, V trunk symmetry showing AUC of respectively .90 and .92, and ML trunk symmetry with AUC of respectively .76 and .77. Unexpectedly, discriminating abilities of AP trunk symmetry was higher for gait in OA patients compared to patients with chronic stroke (AUC respectively 0.91 and 0.82). This may be a result of between group differences in compensatory strategies and remains to be further investigated.

5.3.4 Choice of classification criterion

There is a common agreement that a certain amount of asymmetry is present in normal gait (Sadeghi et al., 2000), but there is no agreement or gold standard defining a cut-off for pathologic gait asymmetry, requiring intervention. In **Paper II**, a 10% cut-off value is proposed and found valid as a general criterion for pathologic gait asymmetry. An optimal cut-off criterion represents the cut-point at the upper left corner of the ROC curve because this is the point resulting in smallest overall error rate (Streiner and Norman, 2008). However, the proportion of subjects correctly classified into either of two groups will depend on the selected cut-off value (Moe-Nilssen et al., 2008). A lower cut-point may be preferred if the consequences of missing a case false-negative have priority. In contrast, the cut-points may be raised if it is of importance to only involve true-positive cases, compared to miss a false-negative case (Streiner and Norman, 2008).

Improvement in gait symmetry occurred at different time-points and with different ES compared to improvement in gait velocity and self-reported function (**Paper III**). Main effects (change from preoperative to 12 months postoperative test occasions) of V gait symmetry, gait velocities, as well as all categories of self-reported measures showed effect sizes above 0.5, indicating improvement above Cohen's proposed threshold for "enough change". This means that improvement in all gait symmetry measures, except V gait symmetry, seem too low according to the proposed levels of ES referred to by Cohen (1992). However, in **Paper II**, it is proposed that gait asymmetry above 10% indicate pathologic gait asymmetry. Since median AP, V and ML trunk symmetry is reduced from respectively 0.26, 0.15 and 0.13 to respectively 0.09, 0.03 and 0.08, in **Paper III**, this indicates non-pathologic gait symmetry in these measures 12 months postoperatively, even though ES is below 0.5 for most measures. Median values of footfall symmetry measures are below 10% gait asymmetry preoperatively as well as 12 months postoperatively, indicating lower levels of gait asymmetry or a lower number of patients with pathologic footfall asymmetry during gait before and after THR surgery.

6. Summary and conclusions

In conclusion, this thesis supports the need to include evaluation of gait symmetry, gait velocity and self-reported function to achieve a thorough evaluation of gait and functioning post stroke and in patients with hip OA before and after THR surgery. Methodology for gait evaluation in research should be performed and presented in a way that is suitable for clinical evaluation of individual patients (Kvien et al., 2007). The limited applicability of prevailing methodology to assess gait symmetry has lead clinicians to only apply subjective observational gait analysis for practical or cost-effective reasons (Archer et al., 2006). A purpose of this thesis was to increase awareness and knowledge about recently introduced procedures and objective methodology suitable for measuring gait symmetry. The methodology presented in this thesis may be applied in research, in clinical settings and in the patients' home environments. It provides valid and reliable measures of trunk and footfall gait symmetry. One primary outcome measure would be an ideal choice, representing the results of a new intervention or therapy (Bagiella, 2009). However, this thesis supports previous research (Bagiella, 2009) emphasizing the necessity to include more than one outcome measure to provide a thorough clinical evaluation of patients with one-sided affection. Thus outcome measures should include measures of trunk and footfall gait symmetry, gait velocity and self-reported function. Such measures are important to provide a thorough evaluation of function which may be required for the development of individually targeted rehabilitation programs after disease or injury causing one-sided affection.

7. Future research

Several questions have been addressed in this thesis. Additional issues and questions have been identified and should be addressed in future research:

- inconsistencies in the direction of step length asymmetry in patients with hip OA remains to be further explored and described

- further understanding of differences seen in gait symmetry of chronic stroke patients and hip OA patients

- long term follow up studies after THR surgery are needed to display whether gait symmetry improvement continuous after 12 months postoperatively

- examine whether intensive and specific rehabilitation strategies will result in earlier improvement towards gait symmetry in AP, V and ML direction of movement

- examine whether intensive and specific rehabilitation strategies will affect the early improvement seen in self-reported function

- examine whether compensatory movement strategies in post stroke gait may be affected by specific and prolonged gait rehabilitation strategies

- examine whether results from this thesis may be applied to other patient groups with disease or injury causing one-sided affection

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